Hybrid Cloud for Healthcare Data Sharing and Mobile Access

An Architectural Overview

Azumah, Kenneth Kwame; Sørensen, Lene Tolstrup; Tadayoni, Reza

Published in:
Nordic and Baltic Journal of Information and Communications Technologies

DOI (link to publication from Publisher):
10.13052/nbjict1902-097X.2018.009

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Hybrid Cloud for Healthcare Data Sharing and Mobile Access: An Architectural Overview

Kenneth Kwame Azumah*, Reza Tadayoni
and Lene Tolstrup Sørensen

Centre for Communications, Media and Info. Technologies, Aalborg University Copenhagen, Denmark
E-mail: kka@cmi.aau.dk; reza@cmi.aau.dk; ls@cmi.aau.dk
**Corresponding Author*

Received 30 October 2018;
Accepted 07 December 2018

Abstract

A hybrid cloud computing architecture that places the mobile device or thin clients first is the logical choice especially in regions with low fixed broadband but high mobile penetration rates. The hybrid cloud model combines the benefits of computing resource elasticity in the public cloud whilst maintaining control of sensitive data and mission-critical applications mainly in a private cloud infrastructure. One industry that stands to benefit from extending mobile computing with hybrid cloud infrastructure is the healthcare industry where clinicians need the ability to access healthcare data from different locations and across multiple devices. This paper identifies a hybrid cloud architecture to support mobile device access and satisfy specific business requirements using the case of a selected hospital in Ghana. In the design of the hybrid cloud architecture the functional and non-functional viewpoints are considered using a case study where the selected hospital is used to conceptually define the requirements and set-up of a hybrid cloud architecture. The case study approach is used to illustrate the practical challenges and limitations for a hybrid cloud architecture in a developing country. The suitability of the design was validated using the metrics of availability, reliability, response time and throughput.

Journal of NBICT, Vol. 1, 153–176.
doi: 10.13052/nbjict1902-097X.2018.009

Keywords: Hybrid cloud, cloud architecture, mobile cloud, cloud computing in healthcare.

1 Introduction

A hybrid cloud is a combination of two or more distinct cloud deployment models where the models are either public, private or community clouds [1]. In a state-of-the-cloud survey done by RightScale[1] in January 2016, 95% of worldwide respondents – companies with over 1000 employees – were using cloud and 71% were hybrid cloud adopters [2]. According to RightScale the significant rise in hybrid cloud adoption was mainly due to public cloud users adding private cloud resource pools to their infrastructure. Gartner[2] projected the public cloud services to grow to $208.6 billion in 2016 an increase of 17.2% on 2015 with a domination of hybrid cloud computing scenarios as many traditional IT organisations continued incorporating their existing datacentres into their overall cloud adoption [3]. Cloud implementations in the developing world is also expected to grow, mainly driven by the growing mobile phone penetration rates, especially in sub-Saharan Africa which is projected grow from 43% in 2015 to 51% of total population by 2020 [4–6] and this is signalling the need to make provision for mobile cloud during architectural planning and implementation.

Cloud computing wields great potential to facilitate the running of resource-intensive applications on mobile devices. Smart phones and tablets typically have limitations in memory, storage, computational power and energy capacity which negatively affect users experience when running resource-intensive tasks, specifically those that are computationally, communication or data intensive [7]. Cloud computing offers the possibility of offloading the resource intensive tasks in mobile applications for processing in the resource rich cloud and thereby improve user experience closer to that seen in the desktop computer [8, 9]. Mobile devices continue to grow more powerful in terms of processing power and memory capacity however the battery as a power source has lagged behind in development affecting the overall capacity of the mobile devices to meet user expectations in resource-intensive applications [10].

---

[1]RightScale (http://www.rightscale.com) is a multi-cloud management solutions provider founded in 2006.

[2]Gartner Inc. (http://www.gartner.com) is an IT related research and advisory firm founded in 1979.

One industry that stands to benefit from extending mobile computing with cloud infrastructure is the healthcare industry [11] where clinicians need the ability to access healthcare data from different locations and across multiple devices [12]. Mobile cloud is one way by which mobile devices could be used to access and process electronic health records of patients, to view diagnostic images in various resolutions or collect health data from patients [13]. In Ghana, as in other developing countries, cloud computing and mobile applications and policies are being utilised in the health care sector to mitigate the pressure on clinical facilities and personnel [14, 15]. With the promising potential of cloud computing in developing economies, studies [16–19] have been done to help shape cloud adoption but the appropriateness of a hybrid cloud architecture to meet specific business requirements have received little attention. In the healthcare industry, specific network requirements of availability [12, 20, 21], economic archive storage capacity [20, 22], mobile device accessibility [12, 13], regulatory compliance [20, 23] and security [24] demand particular characteristics [25] in the hybrid cloud. From the aforementioned trends, a hybrid cloud computing architecture that places the mobile device or thin clients first is the logical choice especially in regions with low fixed broadband but high mobile penetration rates. Further, Griebel et al. [26] categorised articles written on MEDLINE into six topics areas that include availability, storage, mobile access, compliance and security to be high on the list of networking requirements when considering the adoption of cloud computing.

This paper examines the key components of hybrid cloud architecture, specifically a public cloud and on-premise private cloud combination, for supporting mobile device access using the case of a selected hospital in Ghana. The cloud combination affords a level of flexibility which cannot be found in either the public cloud or on-premise private cloud alone: the advantage of elastic scaling out within the public cloud with maximum control of sensitive data in the private on-premise datacentre. In the design of the hybrid cloud architecture the functional and non-functional viewpoints are considered using a case study where the selected hospital is used to conceptually define the requirements and set-up of a hybrid cloud architecture. The case study approach is used to illustrate the practical challenges and limitations for a hybrid cloud architecture in a developing country. The business case for the hybrid cloud adoption is examined and tested against the selected architectural components. A summary of the key approach to designing a suitable hybrid cloud architecture in this paper is to:

- Review state-of-the-art in hybrid cloud architecture with a focus on the non-functional attributes of availability, reliability, response time and throughput.
- Identify the main business requirements (hospital processes) to be executed in the cloud, classify them as workloads and determine how to measure their non-functional requirements also known as quality attributes.
- Determine the architectural components that are needed to make the data in the processes highly available to both internal and external users of the information system.
- Verify that the designed hybrid cloud architecture satisfies the specified non-functional requirements categorised under availability, reliability, response-time and throughput.

The rest of the paper is structured as follows: Section 2 presents the state-of-the-art in hybrid cloud architecture describing work that has been done to improve the performance of hybrid clouds. Section 3 describes the functional and non-functional requirements for the selected case, laying out the criteria for selecting a cloud computing architecture. Section 4 discusses the results of the application of the selected architecture and Section 5 concludes the article.

2 State-of-the-Art in Hybrid Cloud Architecture

2.1 A. Hybrid Cloud Architecture

The hybrid cloud model combines the benefits of computing resource elasticity in the public cloud whilst maintaining control of their sensitive data and mission-critical applications in a private on-premise infrastructure [27–30]. The performance of the cloud combination is an interesting subject of on-going study by many researchers as well as proposed solutions by providers such as VMware, IBM and Microsoft [31–33]. There are a few studies that have yielded strategies and techniques to help improve the overall performance and manageability of hybrid cloud facilities: proactive workload management is a technique treated by Zhang et al. with the presentation of network architecture that handles workload spikes in the on-premise network by directing the excess into a shared or public network in the hybrid cloud [34]. Avresky et al. proposed a framework that used machine learning to manage computing resources especially when IaaS deployed software anomalies are detected [35]. The strategy of the framework they proposed was to continue to receive and redirect virtual workloads to other geographic areas for processing even when deployment anomalies are detected. The afore-going proposed solutions are however not ideal for data-intensive applications in geographic locations where bandwidth costs are relatively high, such in sub-Saharan Africa [12].

Again, software and networking solutions have been put forth by cloud computing providers to improve the overall performance and manageability of the hybrid cloud, particularly to seamlessly bridge on-premise data centres with the public cloud infrastructure. Rackspace's offering of Microsoft Azure [32], IBM's Power8 architecture [31], VMware's Cloud Computing Platform [33] and Amazon's Hybrid Hosting package are some of the competing solutions targeted at large enterprises and SaaS providers however an analysis of the business processes and workloads are needed to determine their suitability in meeting specific business requirements such as in healthcare provider in need of a cold archiving solution. Further, frequent workload transfer between data centres is apt to cost more, both financially and in quality of service especially at regions where the cost of Internet bandwidth is yet reach globally competitive prices [37].

A study that incorporated information processing operations into the design of cloud computing network was done by Haung et al. [38]. They reasoned that analysing the logs of the information systems could offer insights into how to maintain the working efficiency of the cloud platform in general. It however did not address the specificity of the hybrid cloud consisting of an on-premise data centre tethered to a public cloud. Again, a cloud network topology [39] that is able to handle a few hundred ecommerce order entries per minute will not be suited for transactional processing of big data in the order of tens of thousands per second. In order to benefit from a hybrid cloud setup that incorporates the above strategies and techniques, a business must consider its own business processes and constraints laid on its network architecture.

Figure 1 shows a general architecture underlying various adoptions of the hybrid cloud model. The hybrid cloud will increasingly be a preferred deployment model in enterprises for the long term primarily due to the need to support various business operations such as legacy applications running from their already established datacentres [26–28]. Migrating to the cloud takes careful planning and strategy to avoid extensive downtime in production applications or interruptions in services to clients. The cautious approach to public cloud adoption also reflects the need to remain compliant with regulatory provisions such as the HIPAA [40], the HITECH [41] and Sarbanes-Oxley Act [42]. Bandwidth costs are also factors of consideration especially where software applications are data intensive or involve the routine time-sensitive storage and retrieval of large files such as high resolution images or other multimedia files.

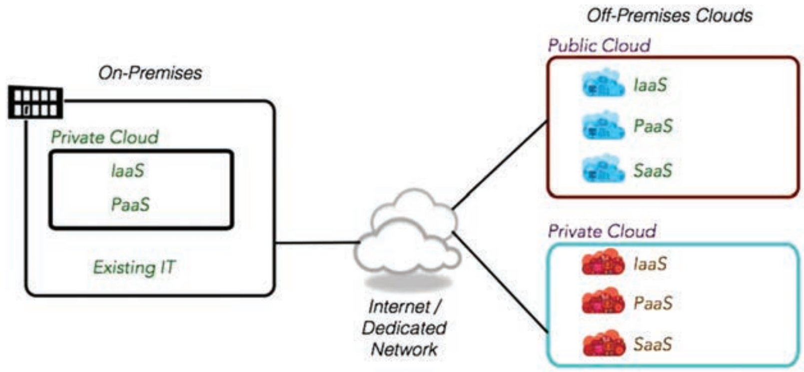


Figure 1 Hybrid Cloud Architecture [27].

Major providers of cloud computing services offer solutions which guarantee compliance with regulations and some level of interoperability between the on-premise data centre and the public cloud, the latter functioning just as an extension of the former. These hardware and software solutions are configurable to meet the data governance needs of businesses and help to route data to preferred storage locations within the hybrid cloud infrastructure. It can be said therefore that a hybrid cloud enables a business to maintain agility through public infrastructure provisioning and enjoy high utilisation in its on-premise facility [31–33].

Cloud computing architecture is often inspired by virtualisation and layerisation of its components that introduce flexibility in deployment to achieve intended purpose. Table 1 shows the basic layered architecture reported as consisting of clients, services, applications, platform, storage and infrastructure: where clients are the access devices; services, applications and platform represent the rendering of computing resources; and storage and infrastructure layers deliver the virtualisation environment [43]. For a hybrid cloud, the architecture is designed using a mix of components within layers, shown in Figure 2 and optimised to suit business goals.

Table 1 Layers in Cloud Architecture [43]

Layer	Function
Clients	End user devices
Services Applications Platform	XaaS: SaaS, PaaS, IaaS
Storage Infrastructure	Data centre netwok fabric, computing and storage

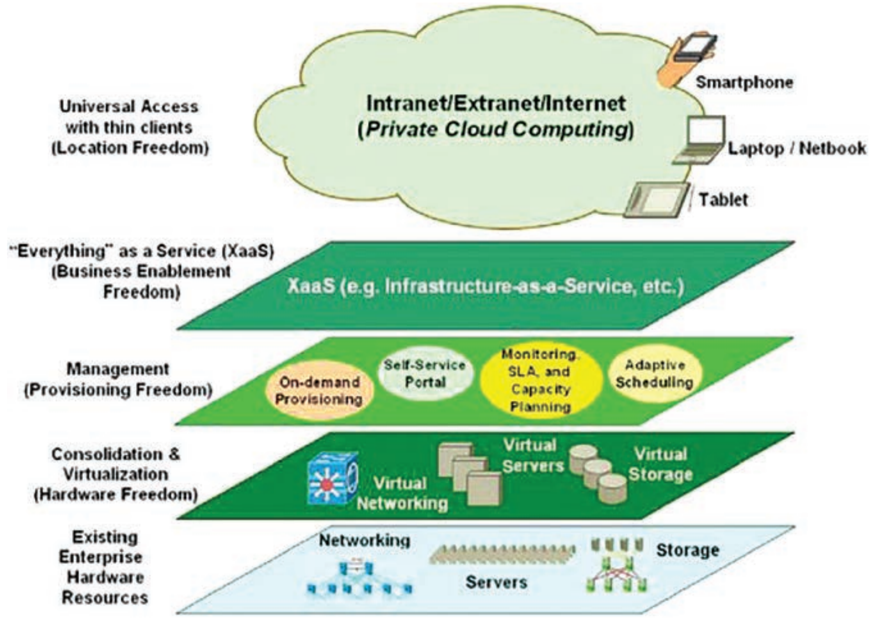


Figure 2 Service-Oriented Infrastructure Framework [45].

A hybrid cloud architecture will generally support business goals if it has a design that meets both the functional and non-functional requirements of the organisation's operations [44]. Figure 2 shows the location of the layers and the description of the relationships between them constituting the functional aspect of the network [44]. The functional view of the network architecture consists of the infrastructure, middleware and software that provide the basis upon which the components are drawn [45]. In deciding what architectural design to adopt, organisations and prospective providers usually base initial discussions on functional views of the required infrastructure.

The view as diagrams facilitates the discussion of concepts such as redundancy, replication, virtualisation and load balancing, all essential elements in making a cloud computing architecture more resilient. The functional view of cloud computing architecture is commonly represented using components grouped by functionality.

The cloud architecture likened to a giant computer is represented with groupings of components as shown in Figure 3. The server module can be thought of as the "brains" or processor of the computer [45]. It consists of virtual machines consolidated onto one or more physical computers. They are

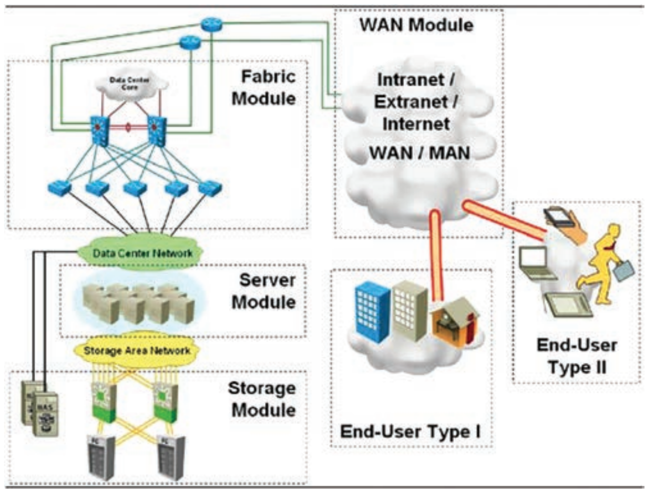


Figure 3 Modular view of cloud computing architecture [45].

interconnected using the internal datacentre network and managed through virtualisation technologies such as the virtual machine monitor or hypervisor. The storage module consists of hard disks arranged in various configurations such as in arrays and using technologies such as RAID to provide redundancy and resilience. Even though the storage module is connected to the server module via the storage-area network, it also connects directly to the internal datacentre network using fast links such as Fibre Channel over Ethernet (FCoE). The fabric module is the core network that integrates the FCoE and other ethernet connections and technologies including facilitating connections outside the datacentre. The WAN module can either be the intranet, extranet or Internet, facilitating connectivity of end-users to the datacentre. Depending of the type of connection, wired or wireless, the end-users can be grouped into the ones in fixed locations and mobile users respectively.

The non-functional view of the network consists of the architecturally significant requirements that must be considered in implementing a hybrid cloud. Because the hybrid cloud architecture facilitates the gradual adoption of cloud computing, constraints are placed on the architecture to ensure there is minimal disruption to existing essential IT services and also to specify non-negotiable requirements in the new network. The non-functional view highlights the architecturally significant requirements affecting the behaviour of the hybrid cloud in supporting specific business goals. For instance in building a hybrid cloud for high availability of data, non-functional specifications to generally consider are capacity and throughput, bandwidth utilisation, offered load, accuracy, efficiency, latency, response and device CPU utilisation. Not all non-functional requirements directly affect the architecture and indicators include requirements that are strict, constraining, limiting or non-negotiable such as requirements associated with high biz value; requirements of high importance to stakeholders; requirements not addressed by existing components; QoS requirements; and requirements with potential for causing budget overruns.

Workload can be defined as a service or collection of code that can be executed or the amount of work that needs to be accomplished by computer resources in a certain amount of time [46]. There are five patterns of workload in cloud computing (shown in Table 2), each focused on achieving specific goals.

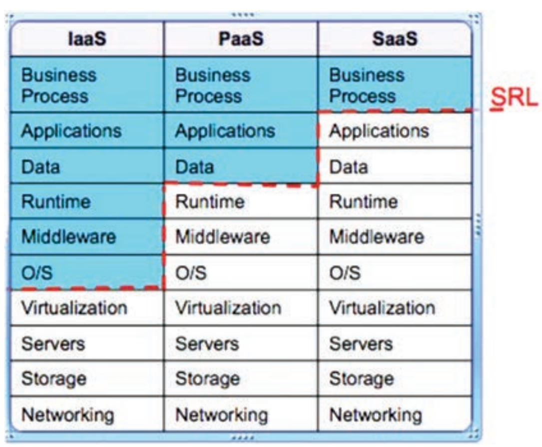
Table 2 Workload Types and their Focus [46, 54]

Workload Type	Workload Pattern	Description	Focus or Goal	Time Sensitivity
Batch workload	Periodic	Designed to operate in background eg. logs	Process large volumes of data in the background	Not time sensitive
Transactional workload	Unpredictable, Continuously Changing	Automation of business processes such as billing/ order processing. If very complex, it is best to let it stay on-premise	Focuses on large volumes of current transactions	Typically requires real-time processing
High performance workload	Unpredictable, Continuously Changing	Used for scientific/ technical and often complex operation. Environment usually must be optimised for them	Has scientific or technical focus	Requires high amounts of compute resources for normal processing
Analytic workload	Periodic, Static	Typically make sense of vast amounts of data across a complex hybrid environment in real-time	Affects large amounts of data for decision making	Depending on the business it could either be batch or real-time
Database workload	Continuously Changing	The most common type of workload. It must be tuned and managed to support the service using the data.	This is highly tuned to application needs	May require specialised hardware integration

Depending on the type of cloud deployment model and architecture, workloads may be adjusted to achieve the required performance. Organisations could have a variety of workloads in their infrastructure which can benefit from a combination of cloud deployment models to save cost. The hybrid cloud can also provide resiliency to overall application availability and faster processing. It thus calls for well-architected and abstracted workloads consisting of multiple services in multiple locations.

The economics of cloud computing are very much affected by the workload requirements. Transactional workloads such as email, collaboration and messaging are well-suited for the public cloud due to features like standardisation, optimisation and scalability. Specialised workloads such the quarterly running of financial reports, a private datacentre is the most appropriate as it is likely the organisation has already invested in the datacentre and hence no special cost-savings moving the workload to the cloud.

Economic benefit can be delivered from the public cloud if there is a need for increased capacity for seasonal handling of workloads, or for software evaluation or system testing. Under these circumstances it will not be economically sound to just build infrastructure due to the short time duration [47]. It is simply better to be up and running within the shortest time and scale-in when the extra capacity is no longer needed. The economic impact and responsibility of running the cloud infrastructure also depends on the service model chosen to handle identified workloads. The service responsibility line in Figure 4 shows the level of economic investment and responsibility required for each cloud service model.



IaaS	PaaS	SaaS
Business Process	Business Process	Business Process
Applications	Applications	Applications
Data	Data	Data
Runtime	Runtime	Runtime
Middleware	Middleware	Middleware
O/S	O/S	O/S
Virtualization	Virtualization	Virtualization
Servers	Servers	Servers
Storage	Storage	Storage
Networking	Networking	Networking

Figure 4 Service Responsibility Line [27].

2.2 Specific Requirements

The business requirements of the hybrid cloud are categorised into the standard engineering requirements: network, archiving, backup and recovery, and compliance and regulatory requirements [27]. The network requirement states the hybrid cloud shall have access and offloading capabilities for mobile devices, wired connection of desktop computers and fibre and radio for WAN interconnection. The compliance and regulatory requirements states the hybrid cloud shall have all personally identifiable information (PII) stored in the private datacentre in compliance with the Data Protection Act 2012 of Ghana. This applies to both data at rest and data in transit. The archiving requirement states the hybrid cloud shall have the capacity to archive inactive records for a specified period of five years. The record in the archive shall be fully retrievable within 30 mins of initiating request. The backup and recovery requirement states the hybrid cloud shall have the capacity to make backup once a week and the system should be fully restored within four hours of the initiating the recovery process. On the mobile access and offloading requirement, the network architecture is further enhanced to support mobile computing where mobile devices offload resource intensive tasks to the hybrid cloud. The hybrid cloud is thus configured to provision resources in the public cloud whenever workloads in the datacentre exceed a maximum threshold. The functional requirements culminate in a hybrid cloud design whose suitability to meet the peculiar requirements of a healthcare computer network is determined by conducting metric measurements involving availability, reliability, response time and throughput [25]. To serve as a reference for the rest of the paper, metric as a term and the quality attributes of the hybrid cloud that is to be measured are introduced.

Metric is defined by NIST as "a standard of measurement that defines the conditions and the rules for performing the measurement and for understanding the results of a measurement" [48]. Availability refers to the capability for introduced redundancies to mask errors and failures that occur in the hybrid cloud system and ensure continuous running of processes [25]. Reliability "Refers to the ability to ensure a continuous process of the program without loss". It is a measure of how reliably a system can recover after failure. The reliability metric category has as important measures the Mean Time To Recovery (MTTR) – how long it takes for a system to recover from failure, Mean Time Between Failures (MTBF) – amount of time that elaspsed between failures and Recovery Time Objective (RTO) – determines how long the entire system is down [25]. Response Time: "This is defined as the time it takes for any workload to place a request for work on the virtual environment and for the virtual environment to complete the request" [49]. Other synonyms for this metric are agility and adaptability [25]. Response time has a direct impact on application performance and availability in the cloud.

Throughput "refers to the performance of tasks by a computing service or device over a specific period" [49]. The metric category is used for measuring rate of transactions as well as the rate of data transported – in bits per second.

The workload defined as the amount of work that needs to be accomplished by computer resources in a certain amount of time [46] is used as the basis for measuring the metrics.

In the next section, the high level requirements are discussed in terms of the preceding networking requirements.

3 The Case of the Selected Hospital

This section describes the functional and non-functional requirements of a hybrid cloud infrastructure that can support data access and clinical operations of the case study. The process model (flow of data) of the hospital and user characteristics is first presented to give an overview of the services that depend on the cloud infrastructure. The networking requirements that best support the process model are then determined with discussion of the various components. The areas of networking requirements to be discussed are availability, economic archive storage capacity, mobile device accessibility, regulatory compliance and security.

3.1 The Hospital

The selected case in Ghana has nine facilities geographically spread across a city. The clinics function as centres of primary healthcare and the hospitals serve as referral facilities if further treatment is required. Patient records are accessible from any facility location by authorised hospital and clinic staff. The records are typically composed of bio-data, diagnoses information, laboratory and radiology investigation results, prescriptions and billing information. The radiology investigations result in the production of high resolution medical images that need to be stored as part of the patient history. High resolution videos are stored on the local network aside the patient records and used to facilitate in-house training of staff. Some other workloads cover administrative processes of the hospital such as human resources, accounting, maintenance management and internal VoIP communication.

The network is accessible by external users for rendering various complementary services. In situations of referral of patients to any of the neighbouring national and regional hospitals, the external specialist is able to access the hospital's corporate network to retrieve the patients' medical history especially in an emergency where the physical folders are not immediately available. Medical insurance companies access a read-only version to vet the medical bills of patients who have policies with them. The general idea is to grant them minimal access to verify prescriptions and other treatment on the basis of the diagnoses given; and raise queries on any billing information that raises doubts about policy compliance. The ambulatory services whilst enroute to the hospital with a sick patient access their electronic records to improve emergency treatment. Access to the data is by a mix of desktop computers and mobile devices typically smartphones and tablets. The performance of the hospital information system in handling such workloads depends on the server workload and bandwidth especially for access outside of the corporate network.

The hospital information system is hosted on datacentre servers located in one of the Hospital buildings. The data centre consists of two rack-mount servers having a total RAM of 64 GB, 2 TB of hard drive space with an additional Network Attached Storage (NAS), and multi-core processors. A hypervisor installed manages four virtual servers that handle the hospital information system, HR, accounting information and database management systems, VoIP gateway services and network management tools. Laboratory and radiology equipment connect directly to the hospital information system via a multi-layer switch in a machine-to-machine communication.

High availability as a network requirement is embodied in the redundancies of the services and their provisioning from public providers with self-healing infrastructure [50, 51]. Availability ensures access to the patient and administrative data at all times taking into consideration the unpredictable nature of the public cloud access. Bandwidth remains a critical factor in connecting two or more clouds together. Significant data movement between the public cloud and the on-premise data centre constrains the corporate internet in terms of cost and bandwidth with the latter resulting in increased latency from transmission queues on the public cloud and overall unpredictable quality of service. The design of the hybrid cloud infrastructure must thus ensure minimal intervening equipment in the path of data packets to generally minimise the transmission times of its relaying or forwarding. On the software side, dynamic caching, compression and pre-fetching are some of the web acceleration technologies that help improve end user connectivity.

If an application however is chatty and requires loads of data transfer across clouds, then adopting cloud computing generally becomes a difficult decision.

Storage as a requirement facilitates the archiving of patient health records in the hybrid cloud design. The physical location of storage in a hybrid cloud is an essential factor in determining the overall cost of owning and maintaining the data. Though new technologies enable storage of more volumes of data at lower costs, the velocity of generating new data continues to rise with the prolific integration of IoT into business operations. Thus the preparation of the data centre for IoT will need high performance redundant connectivity with the LAN, making use of Fibre Channel or Fibre Channel over Ethernet as connections between the servers and SAN with the datacentre. In designing a hybrid cloud infrastructure, the possibility of having a backup and disaster recovery setup without the typical associated upfront costs is an advantage and a quick, reliable data backup and restoration plan lies at the heart of system availability. The cloud offers elastic resource provision that leaves hospital administrators to focus on the core business of providing healthcare. On which side of the hybrid cloud to store the information system data is one decision that impacts the overall performance of the system and is constrained by data governance policies of the organisation.

Regulation in Ghana [52] also enjoins healthcare institutions to keep archived electronic patient records for a minimum period of five years. This requires an archiving of old data to reduce the operational load on the central databases. Depending on the frequency of update of the archival data, active, cool and cold archiving may be chosen. The colder the archive the slower the retrieval and the less expensive it is. Block storage on the other hand is fast to access with low latency but also more expensive per megabyte of storage space and bandwidth. One other inexpensive option to archiving is to use the tape though it can be slow in both saving and retrieval of data.

Security was the next priority in the design that identified each user in the network for appropriate and authorised access whilst guarding against the loss and alteration of data. The measures of security: confidentiality, integrity, authenticity and availability were to be factored into the design using mechanisms and controls to safeguard or improve the security. The level of insecurity was to be measured using vulnerabilities, threats and risks of migrating the existing system to the hybrid cloud. Again the new network had to be evaluated for possible attacks from hidden threat agents such as the anonymous attacker, malicious service agent, the trusted attacker and the malicious insider. Security embodies the mitigation of possible threats and vulnerabilities that can arise if safeguards are not put in place. Compliance deals with the application of regulatory policies to electronic data transactions within the information system. For the hospital, health data was to be held private and confidential and especially ensuring personally identifiable information are protected.

The hybrid cloud introduces complexity into the corporate network and departs from the traditional singular application tools with which IT staff are familiar. The public cloud has a different set of management tools for monitoring, provisioning and decommissioning. It is highly desirable to reduce the cost of administration and increase staff efficiency by having one application that administrators can use but there are few management tools that can efficiently and effectively administer both the public and the private cloud.

Finally, to support mobile devices, the mobile cloud computing paradigm has to be factored into the overall design of the hybrid cloud architecture. The mobile devices offload heavy tasks into the cloud system in order to conserve its local resources especially its limited battery life [7, 8]. The connection to the cloud system is typically via Wi-Fi however other connection methods such as Bluetooth and the regular cellular data packages may be employed.

3.2 The Requirements for a Hybrid Cloud in the Hospital

For the selected case of the hospital, metric values are provided as thresholds for acceptable performance and to support mobile access. It is required that the hybrid cloud have a link availability of 99.90% which translates to 526 mins a year in downtime. Availability in the case of the Hospital is defined based on the weekly user experience of clinical staff interacting with the hospital information system and with a maximum allowable downtime of 10.11 mins per week. This in effect implies the information system should be available for access 99.9% of all the time within the year and any cumulative downtime of about 526 mins or more means the systems is below the required availability threshold. The hybrid cloud introduces more redundancies both at the network level (LAN and WAN) and the application level (Application server, Web server and Database server) to ensure services are available when needed.

Reliability in the hybrid cloud refers to the "engineered availability" [53] of the components and setup in terms of not failing for a period of time: Mean Time To Failure (MTTF); not failing frequently: Mean Time Between Failures (MTBF) and how long it takes to recover from failure: Mean Time To Recovery/Repair (MTTR). The "measured availability" is the actual measurement performed on the engineered setup and components: calculated as MTBF/(MTBF + MTTR) [53] and is required to have a value not less than 99.5% in the hospital network.

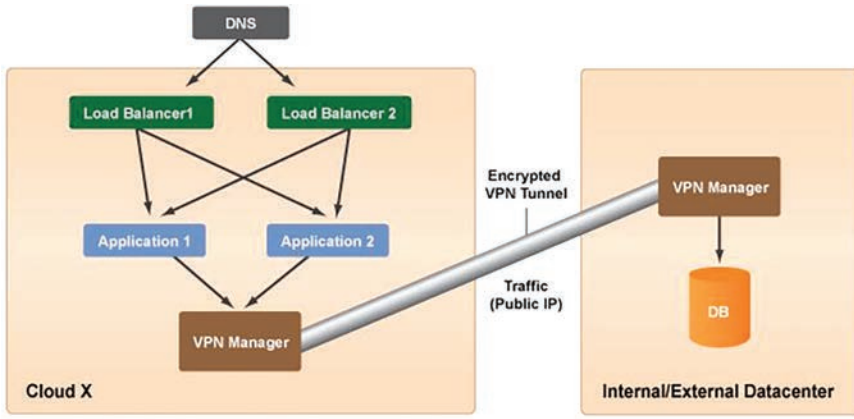


Figure 5 Hybrid Cloud to enhance availability and ensure regulatory compliance [55].

The response time is taken from the perspective of the application response time (ART) which is the sum of the network response time (NRT) and the transaction response time (TRT). By separating the time elapsed due to the network from that generated by the application itself, it is possible to determine the response time of the hybrid cloud network alone. Baseline measurements performed during peak and off-peak times in the WAN portion of the hybrid cloud facilitate more stable values due to greater control over the network components in the WAN and datacentre.

Throughput is measured as the quantity of data (bits) transmitted in one second between the hospital applications server and the client computer. The requirement in the hospital is to have the datacentre network deliver at close to gigabit LAN rates of 10 Mbps at non-busy periods and 5 Mbps at peak usage for over 500 users.

3.3 On-site Requirements Information

The connection of the hospital WAN to the public cloud resulted in a hybrid cloud shown in Figure 5 through which each hospital branch accesses both the internet and the intranet. The VPN through the internet has the datacentre dedicated bandwidth of 10 Mbps whilst the branches of the hospitals had dedicated bandwidths of 2 Mbps. During measurement of the selected metrics the Wireshark network protocol analyser was employed in measuring the throughput and Telerik Fiddler a web debugging tool was used to measure the response times of the network.

During the two month period of measurement, the network experienced downtimes on average every fourth day for an average period of 4 mins

```
Request Count:   1
Bytes Sent:      919        (headers:919; body:0)
Bytes Received:  1,092,981        (headers:289; body:1,092,692)

ACTUAL PERFORMANCE
--------------
ClientConnected:      04:33:01.208
ClientBeginRequest:   04:34:02.408
GotRequestHeaders:    04:34:02.408
ClientDoneRequest:    04:34:02.408
Determine Gateway:    0ms
DNS Lookup:           0ms
TCP/IP Connect:       0ms
HTTPS Handshake:      0ms
ServerConnected:      04:33:33.027
FiddlerBeginRequest:  04:34:02.408
ServerGotRequest:     04:34:02.412
ServerBeginResponse:  04:34:03.818
GotResponseHeaders:   04:34:03.818
ServerDoneResponse:   04:34:04.432
ClientBeginResponse:  04:34:04.432
ClientDoneResponse:   04:34:04.432

       Overall Elapsed:     0:00:02.024

RESPONSE BYTES (by Content-Type)
--------------
text/html: 1,092,692
~headers~: 289
```

Figure 6 Response times as measured with Fiddler.

giving a measured availability of (5760 mins / (5760 + 4 mins)) = 99.9306%. Figure 6 shows the average response time experienced in running the hospital applications: 1,092,692 bytes transferred from server in 4.432–3.818 = 614 milliseconds giving a throughput of about 1.69 Mbps. An average of 1.35 Mbps was experienced transferring small radiology images from the server to a client computer.

4 Results and Discussion of Hybrid Cloud Design

This section presents the architectural design resulting from the consideration of requirements that will support the peculiar business goals of the case study. The objectives of the architecture were to introduce elements of design that will give high availability, storage, mobile access, compliance and security to clinical data and operations using the hybrid cloud.

The measured quality metrics were well within the requirements validating the introduction hybrid cloud computing into the hospital network. To further ensure availability of services on the hybrid cloud, redundancy was built into the overall architecture, introducing an extra load balancer in the network, multiple servers in an array and database replication apart from the snapshot backups taken at regular intervals.

Accessing and processing of healthcare data on mobile devices was facilitated by the server array which allows the spawning of application instances to handle tasks offloaded from resource poor mobile devices. The extra load balancer ensured that incoming requests for processing healthcare data are handled by a highly available server within the datacentre or requests are redirected to the public cloud when fixed resources are low on capacity.

Storage requirements were fulfilled with a combination of replication in the master database in the on-premise datacentre and a pay-per-use public cloud storage. The pay-per-use storage in the public cloud was introduced to cost-effectively archive old patient records and clinical history such that retrieval was achieved in minimal times. Bandwidth costs were thus saved when cold data was pushed into the cloud and more active was retained on the data centre servers. The cost savings were further augmented with a VPN tunnel to meet the security and compliance requirements of the hybrid cloud infrastructure.

5 Conclusion

The paper looked into how to architect a hybrid cloud infrastructure to enhance information sharing whilst supporting mobile device access. A case of a hospital in Ghana which had a unique need for hybrid cloud adoption was examined and the architectural redesign of their existing facilities was found to enhance support for clinical operations across all their facilities.

Hybrid cloud as a growing trend is expected to shape the cloud computing landscape as the interoperability challenges associated with its adoption are addressed. Inroads on Software Defined Networks (SDN) and Software Defined Storage (SDS) will further culminate in smoother hybrid cloud management and easier aggregation of control onto a single pane of glass. More and more software would be born cloud-ready to scale horizontally on demand and interoperate with other software via microservices architecture.

With adequate mobile device centred planning of hybrid cloud computing infrastructure, more organisations in the developing world can improve data sharing among its key stakeholders and the increasingly mobile-savvy clientele. Leveraging on cloud computing technology and the high mobile phone penetration rates is an interesting way to transform existing corporate data centres into data sharing platforms for socio-economic growth, especially in sub-Saharan African economies.

References

[1] Mell, P., and Grance, T. (2011). The NIST definition of cloud computing.
[2] 'Cloud Management Software'. [Online]. Available: http://www.rightscale.com/products-and- services/products/cloud-management
[3] 'Gartner Says Worldwide Public Cloud Services Market to Grow 17 Percent in 2016'. [Online]. Available: http://www.gartner.com/newsroom/id/3443517 [Accessed: 31-Dec-2016].
[4] GSMA, 'GSMA Mobile Economy 2016'. [Online]. Available: http://www.gsma.com/mobileeconomy/ [Accessed: 20-Dec-2016].
[5] Kelly Hill, 'Cloud computing emerging in Africa – RCR Wireless News', 2015. [Online]. Available: http://www.rcrwireless.com/20151023/featured/cloud-computing-in-africa-tag6 [Accessed: 02-Jan-2017].
[6] 'Cisco Global Cloud Index: Forecast and Methodology, 2015–2020,' 2016.
[7] Liu, F., Shu, P., Jin, H., Ding, L., Yu, J., Niu, D., and Li, B. (2013). Gearing resource-poor mobile devices with powerful clouds: architectures, challenges, and applications. *IEEE Wireless communications,* 20(3), 14–22.
[8] Qureshi, S. S., Ahmad, T., and Rafique, K. (2011). Mobile cloud computing as future for mobile applications-Implementation methods and challenging issues. In *2011 IEEE International Conference on Cloud Computing and Intelligence Systems (CCIS),* (pp. 467–471). IEEE.
[9] Fernando, N., Loke, S. W., and Rahayu, W. (2013). Mobile cloud computing: A survey. *Future generation computer systems,* 29(1), 84–106.
[10] Nawrocki, P., and Reszelewski, W. (2017). Resource usage optimization in mobile cloud computing. *Computer Communications,* 99, 1–12.
[11] Hanen, J., Kechaou, Z., and Ayed, M. B. (2016). An enhanced healthcare system in mobile cloud computing environment. *Vietnam Journal of Computer Science,* 3(4), 267–277.
[12] Neyem, A., Carrillo, M. J., Jerez, C., Valenzuela, G., Risso, N., Benedetto, J. I., and Rojas-Riethmuller, J. S. (2016). Improving Healthcare Team Collaboration in Hospital Transfers through Cloud-Based Mobile Systems. *Mobile Information Systems*.
[13] Wu, H., Wang, Q., and Wolter, K. (2013). Mobile healthcare systems with multi-cloud offloading. In *2013 IEEE 14th International Conference on Mobile Data Management (MDM),* (Vol. 2, pp. 188–193).
[14] Asabere, N. Y. (2012). mMES: a mobile medical expert system for health institutions in ghana. *International Journal of Science and Technology,* 2(6), 333–344.

[15] Dumiak, M. (2012). E-health's future frontiers., Bull. World Health Organ., 90(5), pp. 328–329.
[16] Yuvaraj, M. (2016). Determining factors for the adoption of cloud computing in developing countries: A case study of Indian academic libraries. *The Bottom Line*, 29(4), 259–272.
[17] Sharma, S. K., Al-Badi, A. H., Govindaluri, S. M., and Al-Kharusi, M. H. (2016). Predicting motivators of cloud computing adoption: A developing country perspective. *Computers in Human Behavior,* 62, 61–69.
[18] Dahiru, A. A., Bass, J. M., and Allison, I. K. (2014). Cloud computing: adoption issues for sub-Saharan African SMEs.
[19] Gangwar, H., Date, H., and Ramaswamy, R. (2015). Developing a cloud-computing adoption framework. *Global Business Review*, 16(4), 632–651.
[20] Hu, Y., Lu, F., Khan, I., and Bai, G. (2012). A cloud computing solution for sharing healthcare information. In *The 7th International Conference for Internet Technology and Secured Transactions (ICITST).* IEEE.
[21] Kuo, Y. H., Jeng, Y. L., and Chen, J. N. (2013). A hybrid cloud storage architecture for service operational high availability. In *Computer Software and Applications Conference Workshops (COMPSACW), 2013 IEEE 37th Annual* (pp. 487–492). IEEE.
[22] Wang, L., and Alexander, C. A. (2013). Medical applications and healthcare based on cloud computing. *International Journal of Cloud Computing and Services Science*, 2(4), 217.
[23] Regola, N., and Chawla, N. V. (2013). Storing and using health data in a virtual private cloud. *Journal of medical Internet research*, 15(3).
[24] Gavrilov, G., and Trajkovik, V. (2012). Security and privacy issues and requirements for healthcare cloud computing. *ICT Innovations,* 143–152.
[25] Bardsiri, A. K., and Hashemi, S. M. (2014). Qos metrics for cloud computing services evaluation. *International Journal of Intelligent Systems and Applications,* 6(12), 27.
[26] Griebel, L., Prokosch, H. U., Köpcke, F., Toddenroth, D., Christoph, J., Leb, Engel, I., and Sedlmayr, M. (2015). A scoping review of cloud computing in healthcare. *BMC medical informatics and decision making*, 15(1), 17.
[27] Cloud, C. (2016). Standards Customer Council, *Practical Guide to Hybrid Cloud Computing*, pp. 29–31.
[28] Hill, R. Hirsch, L. Lake, P. and Moshiri, S. (2013). Guide to Cloud Computing. London: Springer London, pp. 7–8, 129–133.

[29] Waschke, M. (2015). 'How clouds hold IT together: integrating architecture with cloud deployment', Apress, pp. 112–113.
[30] Srinivasan, S. (2014). Cloud Computing Basics. New York, NY: Springer New York, pp. 6–7.
[31] 'The Hybrid Cloud Built to Perform with POWER8 in IBM SoftLayer,' 2016. [Online]. Available: https://www-304.ibm.com/events/tools/interconnect/2016ems/REST/presentations/PDF/InterConnect2016l_2751.pdf [Accessed: 14-Nov-2016].
[32] 'The Hybrid Cloud and Microsoft Azure,' 2015. [Online]. Available: http://docs.media.bitpipe.com/io_12x/io_122367/item_1162106/RS_HybridAzurewhitepaper_v2.pdf [Accessed: 14-Nov-2016].
[33] 'Cloud Management Platform: VMware.' [Online]. Available: http://www.vmware.com/solutions/virtualization/cloud-management.html [Accessed: 13-Nov-2016].
[34] Zhang, H., Jiang, G., Yoshihira, K., and Chen, H. (2014). Proactive workload management in hybrid cloud computing. *IEEE Transactions on Network and Service Management*, 11(1), 90–100.
[35] Avresky, D. R., Di Sanzo, P., Pellegrini, A., Ciciani, B., and Forte, L. (2015). Proactive scalability and management of resources in hybrid clouds via machine learning. In *2015 IEEE 14th International Symposium on Network Computing and Applications (NCA)*, (pp. 114–119). IEEE. Friday, December 14, 2018 at 2:54 pm.
[36] Maaref, S. (2012). Cloud computing in Africa situation and perspectives. *Telecommun. Dev. Sect.-ITU*, 70.
[37] Numbeo, 'Price Rankings by Country of Internet (10 Mbps, Unlimited Data, Cable/ADSL) (Utilities (Monthly))'. [Online]. Available: https://www.numbeo.com/cost-of-living/country_price_rankings?itemId=33 [Accessed: 02-Jan-2017].
[38] Haung, K. Z., Chen, Y. S., and Chung, Y. K. (2011). Perspectives on process mining within cloud computing. In *2011 3rd International Conference on Advanced Computer Control (ICACC)*, (pp. 656–660). IEEE.
[39] Tsugawa, M., Matsunaga, A., and Fortes, J. A. (2014). Cloud networking to support data intensive applications. In *Cloud Computing for Data-Intensive Applications* (pp. 61–81). Springer, New York, NY.
[40] P. Law, 'Health Insurance Portability and Accountability Act of 1996. Public Law 104–191.' United States statutes at large, 1996. [Online]. Available: https://aspe.hhs.gov/report/health- insurance-portability-and-accountability-act-1996 [Accessed: 10-Oct-2016].

[41] Garner, R. L. (2017). Evaluating Solutions to Cyber Attack Breaches of Health Data: How Enacting a Private Right of Action for Breach Victims Would Lower Costs. *Ind. Health L. Rev.*, 14, 127.
[42] 'The Sarbanes-Oxley Act 2002.' [Online]. Available: http://www.soxlaw.com/
[43] Kalapatapu, A. Sarkar, M., and Khazaei, H. 'Cloud Computing,' in Cloud Computing, CRC Press, 2011, pp. 3–29.
[44] McCabe, J. D. (2007) Network analysis, architecture, and design. Burlington: Elsevier/Morgan Kaufmann Publishers.
[45] Smoot, S. R., and Tan, N. K. (2011). Private cloud computing: consolidation, virtualization, and service-oriented infrastructure. Elsevier.
[46] Hurwitz, J. S., Kaufman, M., Halper, F., and Kirsch, D. (2012). Hybrid cloud for dummies. John Wiley & Sons.
[47] Laatikainen, G., Mazhelis, O., and Tyrvainen, P. (2016). Cost benefits of flexible hybrid cloud storage: Mitigating volume variation with shorter acquisition cycle. *Journal of Systems and Software*, 122, 180–201.
[48] NIST Cloud Service Metrics Sub Group, 'Cloud Computing Service Metrics Description,' 2015.
[49] 'Cloud Services Industry's 10 Most Critical Metrics - Guiding Metrics.' [Online]. Available: http://guidingmetrics.com/content/cloud-services-industrys-10-most-critical-metrics/ [Accessed: 20-Feb-2017].
[50] Dai, Y., Xiang, Y., and Zhang, G. (2009). Self-healing and hybrid diagnosis in cloud computing. In *IEEE International Conference on Cloud Computing*. (pp. 45–56). Springer, Berlin, Heidelberg.
[51] 'Do you have a self-healing cloud? – Cloud computing news'. [Online]. Available: https://www.ibm.com/blogs/cloud-computing/2012/03/do-you-have-a-self-healing-cloud/ [Accessed: 22-Jan-2017].
[52] 'Data Protection Commission |protecting the privacy of the individual & personal data.' [Online]. Available: https://www.dataprotection.org.gh/ [Accessed: 21-Jan-2017].
[53] 'Availability Measurement.' [Online]. Available: http://www.cisco.com/networkers/nw04/presos/docs/NMS-2201.pdf [Accessed: 04-Mar-2017].
[54] Fehling, C., Leymann, F., Retter, R., Schupeck, W., and Arbitter, P. (2014). *Cloud computing patterns: fundamentals to design, build, and manage cloud applications.* Springer Science & Business Media.
[55] RightScale, 'Cloud Computing System Architecture Diagrams.' [Online]. Available: http://docs. rightscale.com/cm/designers_guide/cm-cloud-computing-system-architecture-diagrams.html

Biographies

Kenneth Kwame Azumah is Ph.D. fellow at CMI (Center for Communication, Media and Information Technologies) at Aalborg University Copenhagen, since autumn 2016. He attended the Kwame Nkrumah University of Science and Technology, Ghana where he received his B.Sc. in Computer Science in 2001. Azumah received an M.Eng. in Electrical Engineering and Information Technology from Deggendorf Institute of Technology, Germany in 2009 and an MBA from the Blekinge Institute of Technology, Sweden in 2011. He is currently working to complete his Ph.D. at Aalborg University Copenhagen where his research centers on hybrid cloud computing with process mining.

Reza Tadayoni is associate professor at CMI (Center for Communication, Media and Information Technologies) at Aalborg University. He holds an M.Sc.E.E. from DTU (Danish Technical University) specialized in broadband communication, and holds a PhD from DTU in the field of media convergence. His main research focus is on the ICT development and media convergence. Reza Tadayoni has participated in a number of Danish, European and international research projects and he has supervised a number of PhD projects and master and bachelor thesis, and he has published +100 of scientific papers and research reports.

Lene Tolstrup Sørensen is associate professor at CMI (Center for Communication, Media and Information Technologies), Electronic Systems, at Aalborg University Copenhagen. She holds a Ph.D. in Engineering from DTU (Technical University of Denmark) and has specialized in Interaction Design, and software engineering and usable privacy. Sørensen has been a member of IEEE for many years. Furthermore, within the last 10 years, she has worked closely with the Wireless World Research Forum on for example requirement analyses of new technologies. Sørensen has published more than 100 scientific papers, reports and books.